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EFFECT OF X-RADIATION ORIGINATING IN A FLARE ON THE D-REGION OF THE IONOSPHERE

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ABSTRACT

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This paper discusses the distorted course of electron density in the F-region of the ionosphere, caused by X-radiation in the 1-10 Å wave band. It is found that the distribution curve of excess ionization has a monotonic character. For all examined forms of the energy distribution function the most significant distortions of the electron density curve take place in the 80 km altitude level and below. It is doubtful that any other form of the curve of electron density distribution would be possible in time of sudden ionospheric disturbances (SID)

COVER-TO-COVER TRANSLATION

The substantial variations in the distribution of electron density N (O, z) in the D-region of the ionosphere under the effect of

* Vozdeystviye rentgenovskogo izlucheniya vspyshki na oblast'D ionosfery.

the ionizing radiation originating in the chromospheric flares result in an increase of radiowave absorption, in a sudden increase in intensity of atmospheric disturbances and in the variation in the phase path of radiowaves reflected from the ionosphere. But the character of deformation of N (0, z) distribution curve during sudden ionospheric disturbances (SID) is a question still unresolved at the present time. Rocket measurements [1] and indirect methods of investigation of the D-region of the ionosphere [2, 3] point to the possibility of electron density increase as a result of the effect of X-radiation originating in the flares. Thus, the attempt to obtain a certain representation of the distribution of excess ionization in the ionosphere region from 50 to 100 km under the action of flare ionizing radiation in the 1 to 10 Å waveband appears to be appropriate.

DEPENDENCE OF THE ION FORMATION FUNCTION ON ALTITUDE

The ion-formation function for a monochromatic radiation (in case of a vertical incidence of the flux and without taking account of Earth's curvature) is described by the correlation [4] :

$$I(z) = \frac{\sigma n(z)}{\varepsilon_i} S_\infty \exp\left[-\sigma \int_z^\infty n(z)\, dz\right], \qquad (1)$$

where σ is the effective photoionization cross section; n (z) is the desnity of ionized particles; S_∞ is the energy flux entering the atmosphere from without; ε_i is the ionization potential.

The value n (z) is the density of neutral particles for the X-radiation in the 1 - 10 Å wavelenegth range. Inasmuch as the altitude dependence of neutral particles in the 50 to 140 km range is well described by the barometric equation [5], we may write

$$n(z) = n_0 \exp\left(-\frac{z-z_0}{H}\right), \quad (2)$$

where H is the altitude brought out; n_0 is the density of neutral particles at the z_0 level from the Earth's surface.

Substituting (2) in (1), we obtain

$$I(z) = \frac{\sigma S_\infty}{\varepsilon_i} n_0 \exp\left\{-\frac{z-z_0}{H} - \sigma H n_0 \exp\left(-\frac{z-z_0}{H}\right)\right\}. \quad (3)$$

But if quantum absorption takes place with a wavelength included in the λ to $\lambda + \lambda d$ range, it is obvious that

$$I(z,\lambda)\, d\lambda = \frac{\sigma(\lambda)\, n(z)}{\varepsilon_i} S(z,\lambda)\, d\lambda.$$

We then may write for a nonmonochromatic radiation in the wavelength range

$$\Delta Q(z) = \int_{\lambda_1}^{\lambda_2} I(z,\lambda)\, d\lambda =$$

$$= \int_{\lambda_1}^{\lambda_2} \frac{\sigma(\lambda)\, S_\infty(\lambda)}{\varepsilon_i} n_0 \exp\left\{-\frac{z-z_0}{H} - \sigma(\lambda) H n_0 \exp\left(-\frac{z-z_0}{H}\right)\right\} d\lambda. \quad (4)$$

It may be seen from (4), that for the computation of the relative variation of $\Delta Q(z)$ with altitude it is necessary to know $S(\lambda)$. The energy distribution $S(\lambda)$ in the interval $\lambda_1 - \lambda_2$ is not ascertained, since the function $S(\lambda)$ is determined by a currently insufficiently studied mechanism of X-ray emission. Thus, we may make for the function $S(\lambda)$ as a zero approximation that $S(\lambda)\Big|_{\lambda_1}^{\lambda_2} = \text{const}$.

In that case

$$\Delta Q(z) = \frac{S_{\infty}}{[illegible]} \int_{\lambda_1}^{\lambda_2} \sigma(\lambda)\, n_0 \exp\left\{-\frac{z - z_0}{H} - \sigma(\lambda)\, H n_0 \exp\left(-\frac{z - z_0}{H}\right)\right\} [illegible] \qquad (5)$$

Let us now find the maximum value of $\Delta Q(z)\,|_{z=z_m}$ from the condition $\frac{d\Delta Q(z)}{dz} = 0$:

$$\Delta [illegible]\,|_{z=z_m} [illegible] \int_{\lambda_1} [illegible] \exp\left\{-\frac{\sigma(\lambda)}{\bar{\sigma}(\lambda)}\right\} d\lambda, \qquad [illegible] \qquad (6)$$

where

$$\bar{\sigma}(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} \sigma(\lambda)\, [illegible]}{\lambda_2 - \lambda_1} = H n_0 \exp\left\{-\frac{z_m - z_0}{H}\right\}.$$

Making use of (5) and (6), we shall find for the relative variation of the quantity $\Delta Q(z)$ with the altitude

$$\frac{\Delta Q(z)}{\Delta Q(z)\,|_{z=z_m}} = \frac{\int_{\lambda_1}^{\lambda_2} \tau(\lambda) \exp\{-\tau(\lambda)\}\, d\lambda}{\int_{\lambda_1}^{\lambda_2} \beta(\lambda) \exp\{-\beta(\lambda)\}\, d\lambda},$$

where

$$\tau(\lambda) = \sigma(\lambda) H n_0 \exp\left\{-\frac{z - z_0}{H}\right\}, \qquad \beta(\lambda) = \frac{\sigma(\lambda)}{\bar{\sigma}(\lambda)}.$$

It may be seen from (7), that if $\tau(\lambda)$ and $\beta(\lambda)$ are known, we may compute the relative variation of the ion-formation function with the altitude. The curves 1 and 2 of Fig. 1 represent the graphs of $\frac{\Delta Q(z)}{\Delta Q(z)\,|_{z=z_m}}$. variations. The values $\sigma(\lambda)$ and those of neutral particle density $n(z)$ at various heights were borrowed from the works [5, 6]. The values

$$\int_{\lambda_1}^{\lambda_2} \tau(\lambda) \exp\{-\tau(\lambda)\}\, d\lambda \quad \text{and} \quad \int_{\lambda_1}^{\lambda_2} \beta(\lambda) \exp\{-\beta(\lambda)\}\, d\lambda$$

were found by numerical integration. The curves 1 and 2 of Fig. 1 have the shape of parabolae with a clearly expressed maximum at 85 km (1) and a shape of parabolae with a clearly expressed maximum at 85 km for the curve 1 and at 61 km for the curve 2. In the first case, the perturbed region stretches from 66 to 100 km, and in the second — from 50 to 73 km (along the 0.4 level).

The next approximation may be the assumption that the X-radiation has a thermal character [1], i.e. that a Plank energy distribution takes place [7].

$$S(\lambda) = \frac{2hc^2}{\lambda^5}\,\frac{1}{\exp\left\{\frac{hc}{\lambda kT}\right\}-1},$$

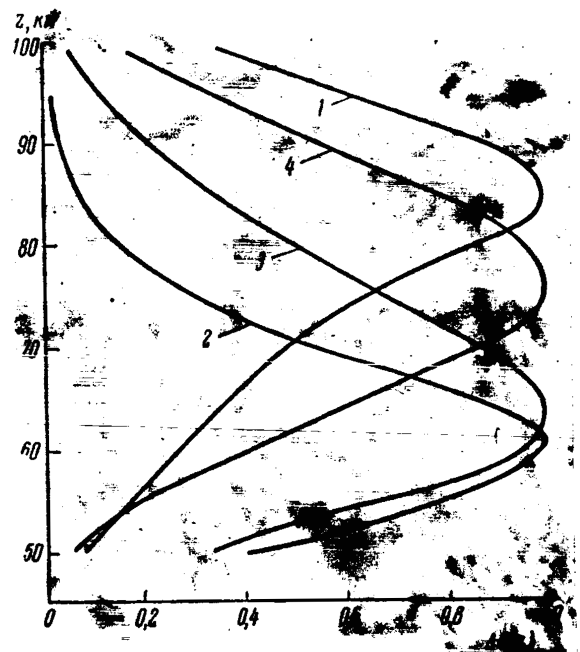

Fig. 1.

Curves 1 and 2 — S (λ) = const, radiation takes place for 1.24 – 10 Å and 1.24 – 2.48 Å
Curves 3 and 4, — S (λ) — Plank, temperature of the radiation region is

where h is the Plank constant, c is the speed of light, λ is the wavelength; T — the body temperature and k — the Boltzmann constant.

Substituting the value of S (λ) in (4), we may compute, as this was done above, the relative variation of $\frac{\Delta Q(z)}{\Delta Q(z)|_{z=z_m}}$ as a function of the altitude. The computation was made for two values of the temperature $T = 10^7$ and $T = 2 \cdot 10^7$ (see Fig. 1) in the waveband 1.24 – 10 Å. The curves 3 and 4 have also the shape of parabolae with a clearly outlined maximum at 64 km (curve 3) and at 75 km (curve 4), with the perturbation region stretching respectively from 50 to 83 and from 60 to 94 km.

DISTRIBUTION OF THE EXCESS IONIZATION AS A FUNCTION OF ALTITUDE

The ionization balance equation, describing the variation of electron density during SID may be written [4]:

$$\frac{dN(t,z)}{dt} = Q(t,z) - \alpha(z)N^2(t,z), \qquad (8)$$

where $Q(t,z) = Q(0,z) + \Delta Q(t,z)$, $Q(0,z)$ is the ion-formation function during the unperturbed state of the ionosphere. $\Delta Q(t,z)$ is the accretion of the ion-formation function, caused by flare's X-radiation.

For a quiescent state of the ionosphere the ionization balance equation had the form

$$\frac{dN(0,z)}{dt} = Q(0,z) - \alpha(z)N^2(0,z). \qquad (9)$$

Substracting (9) from (8), we obtain

$$\frac{d[N(t,z) - N(0,z)]}{dt} = \Delta Q(t,z) - \alpha(z)[N^2(t,z) - N^2(0,z)].$$

We note near the moment of SID maximum a quasistationary state, which may be expressed as

$$\frac{d[N(t,z) - N(0,z)]}{dt} \ll \alpha(z)[N^2(t,z) - N^2(0,z)],$$

and we may admit that

$$\Delta Q(t,z)|_{t=t_m} \cong \alpha(z)[N^2(t,z)|_{t=t_m} - N^2(0,z)]. \qquad (10)$$

Then, for the relative variation $[N^2(t,z)|_{t=t_m} - N^2(0,z)]$ we may write the following equation

$$\varphi(z) = \frac{[N^2(t,z)|_{t=t_m} - N^2(0,z)]}{[N^2(t,z)|_{t=t_m} - N^2(0,z)]|_{z=z_m}} = \frac{\alpha(z)|_{z=z_m}}{\alpha(z)} \frac{\Delta Q(t,z)|_{t=t_m}}{\Delta Q(t,z)|_{t=t_m, z=z_m}} \qquad (11)$$

where z_m is the altitude of the maximum value of $\Delta Q(z,t)|_{t=t_m}$

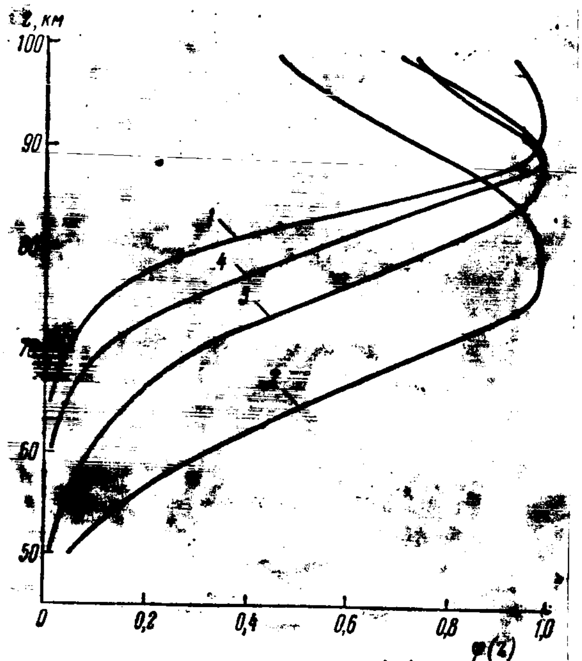

Fig. 2. Variations of $\varphi(z)$ for the corresponding curves of Fig. 1.

Presented are in Fig.2 the graphs of $\varphi(z)$ variation for the corresponding distributions of ion-formation functions. The values of $\alpha(z)$ were borrowed from [8] , as the most comtemporary data on the recombination coefficient. It is rather difficult to reach any conclusions about the character of deformation of the electron density distribution curve at time of SID. However, the quantity $N(t, z)$ may be written in the form

$$N(t, z) = x(t, z) \cdot N(0, z) \qquad (12)$$

where $x(t, z)$ is the relative variation of electron density.

Substituting (11) into (10), and after several transformations, we shall obtain

$$N(t, z) \ldots = \ldots$$ [illegible] (13)

It may be seen from (13), that if the model of the unperturbed ionosphere and the relative electron density variation at the altitude z_m $[\varphi(z)|_{z=z_m} = 1]$ are known, we may constrcut the distribution of excess ionization in time of SID for a specific form $S(\lambda)$ of X-ray radiation.

Fig. 3 shows the diagram of electron density N [illegible] dependence on altitude for the corresponding $\varphi(z)$. The model of the unperturbed D-region, which may be approximately represented by an exponential was borrowed from ref. [4]. The values [illegible]$(t, z)|_{t=t_m, z=z_m}$ were taken such that the perturbations would be about equivalent in their intensity (by the variation of total absorption. It may be seen from Fig. 3 that the character of curve $N(0, z)$ deformation is qualitatively the same for all the different function $S(\lambda)$. All the curves have a monotonic course with no sharply expressed maxima or minima. The significant variations of the curve of electron density $N(0, z)$ ditribution in time of SID take place for the considered forms of the function $S(\lambda)$ below 80 km.

QUALITATIVE ESTIMATES

The question of the origin of X-rays is at present insufficiently studied, but a series of authors [1] still consider that the X-radiation possibly has a thermal character, while it is known that the temperature of the "core" of the flare reaches 5 to 10 million ^{o}K.

The mean value of the variation during SID of the total absorption for the considered cases of X-ray intensity distribution corresponds to the relative increase of electron density $\varkappa(t, z)\Big|_{\substack{t=t_m \\ z=z_m}}$ by not more than 1.3 times. It must also be noted that it is difficult to expect a multifold electron density variation at altitudes of the order of 90 km, as the sensible increase of the E-layer's critical frequency during SID is observed seldom. (see [9]).

For a quantitative appraisal of the variation of total absorption and of energy flux having caused it, the following assumption were made, on the basis of which the electron density distribution was computed, say the value of $N(t, z)|_{t=t_m}$. (see Fig. 3, 1).

1. The spectral distribution of X-ray intensity corresponds to the distribution in the spectrum of an absolutely black body, at a 10^{7} ^{o}K temperature.

2. The initial electron density distribution is the exponential

$$[N(0, z) = 10[illegible]p\,\{0,23\,(z - [illegible]0)\}].$$

3. At the 90 km level the electron density increased 1.3 times.

It may be seen from Fig. 3 (next page) that perturbation took place mainly below 85 km. We plotted the dependence of the absorption factor K (0, z) and K (t, z) on altitude at the 26.7 mc/s frequency on the basis of data on the quantity ν(z) [10]. For such K (0,z) and K (t, z) distribution, it resulted that the total absorption of the quiet D– region at a frequency of 26.7 mc/s was ~ 0.3 db . This agrees well with [11], where the total absorption increased by ~ 1.79 db. in the 50 to 100 km range.

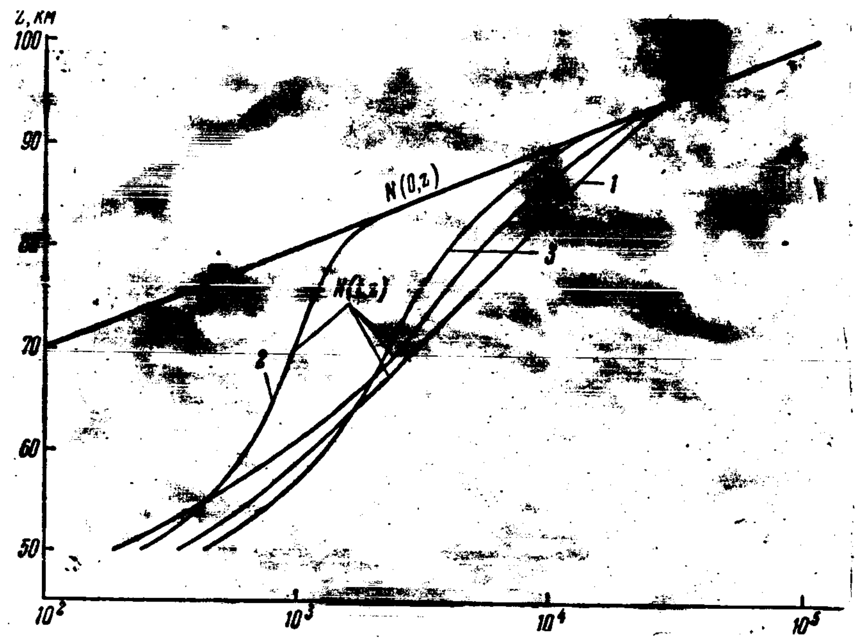

Fig. 3. Dependence on height of electron density
$N(0, z)$, $N(t, z)$
for corresponding values $\varphi(z)$

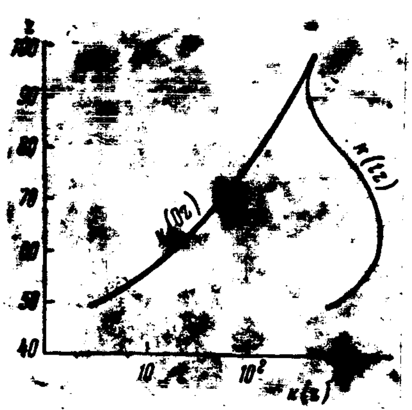

Fig.4. Dependence of the absorption factor on the height, at 26.7 mc/s (in arbitrary units)

Fig. 5 represents the copy of the readings of cosmic radio emission intensity at 26.7 mc obtained by the Crimean Astrophysical Observatory during the SID of 7 August 1960 [12]. At that time a mark 1 flare was taking place on the Sun [13].If we consider that no variation in electron density took place

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above 100 km, then in the absorption maximum (10 38 hrs) the absorption increased by ~ 1.53 db relative to the undisturbed state of the D-region. Thus the deformation of the curve N (0, z) under the effect of X-radiation with a Plank intensity distribution ($T = 10^7\ {}^{\circ}K$) is not in contradiction with the noted effects of absorption increase.

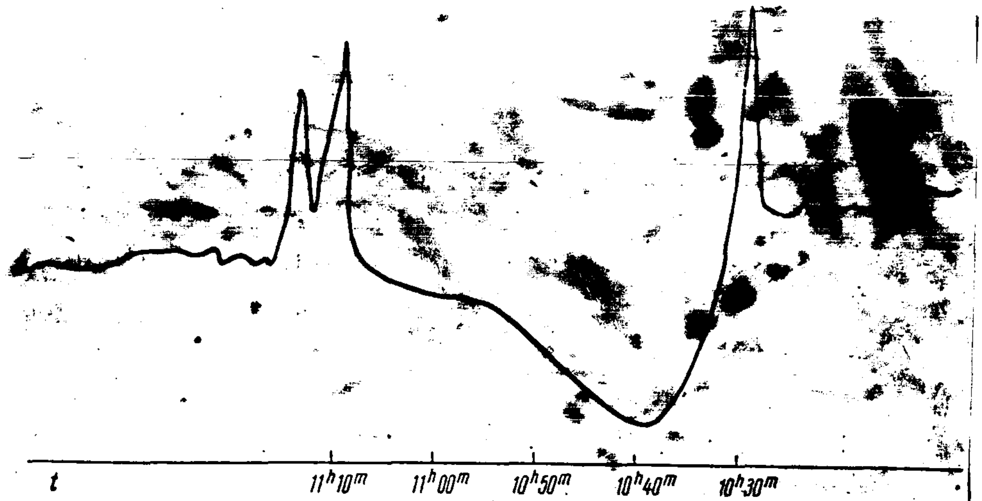

Fig. 5. Copy of the registration of cosmic radio emission in the frequency of 26.7 mc/s during the SID of 7 August 1960.

Utilizing the correlations (10), (12) and (7), we compute the total number of ionization acts in a column of $1 cm^2$ cross section in the whole D-region (from 50 to 100 km), which is

$$Q_{\pi} = 31 \cdot 10^6\ cm^{-2} \cdot sec^{-1}.$$

If we postulate that the mean X-radiation energy in the 1 — 10 Å range, expended on one ionization act in air, $\varepsilon = 32.5$ eV [14], the total ehergy of the flux havung caused the given disturbance will be

$$W = Q_{\pi} \cdot \varepsilon = 1.6 \cdot 10^{-3}\ erg \cdot cm^2 \cdot sec^{-1}$$

This agrees well with the rocket measurement data [1], which give $3 \cdot 10^{-3}$ erg $cm^2 \cdot sec^{-1}$ for the value the flux' energy at 70 km. The measurements took place during a flare of mark 1 intensity.

CONCLUSIONS

1. A significant deformation of the electron density curve takes place in the D-region of the ionosphere under the effect of X-radiation originating in a flare.

2. The curve of excess ionization distribution has a monotonic character.

3. Significant deformations of the curve $N(0, z)$ take place for the considered forms of $S(\lambda)$ at the 80 km altitude level and below.

4. It is doubtful that any other form of the curve of electron dessity distribution during SID is qualitatively possible.

The author considers it its duty to thank N. A. Savich for his valuable counsel at completing this work, and also Yu. I. Vinogradov for his assistance at computations.

****** E N D ******

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